

# Towards $\mu$ -arcsecond spatial resolution with Air Cherenkov Telescope arrays as optical intensity interferometers

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**Abstract.** In this poster contribution we highlight the equivalence between an Imaging Air Cherenkov Telescope (IACT) array and an Intensity Interferometer for a range of technical requirements. We touch on the differences between a Michelson and an Intensity Interferometer and give a brief overview of the current IACT arrays, their upgrades and next generation concepts (CTA, AGIS, completion 2015). The latter are foreseen to include 30-90 telescopes that will provide 400-4000 different baselines that range in length between 50 m and a kilometre. Intensity interferometry with such arrays of telescopes attains  $50\mu$ -arcseconds resolution for a limiting  $m_v \sim 8.5$ . This technique opens the possibility of a wide range of studies, amongst others, probing the stellar surface activity and the dynamic AU scale circumstellar environment of stars in various crucial evolutionary stages. Here we discuss possibilities for using IACT arrays as optical Intensity Interferometers.

## 1. Introduction

Over the past decade, Michelson stellar interferometry has seen some tremendous advances in applicability. It has evolved from a primarily experimental technique towards a general astrophysical observational mode extensively used by the community for galactic and extragalactic science (see the various contributions in these proceedings). Observations with milli arcseconds angular resolution are now routinely performed in the near infrared. Strategic planning of next generation Michelson interferometers should aim for higher resolution, higher sensitivity and image reconstruction capabilities (synthesis or direct imaging). An alternative technique to Michelson interferometry that has the potential of delivering similar scientific products is the technique of intensity interferometry (II). It is able to attain  $\mu$ -arcseconds resolution and provide image synthesis capacity and can be implemented in a cost effective and straightforward instrument.

The principle of II is based on the partial correlation of intensity fluctuations of coherent light beams measured at different points in space or in time. The fluctuations (also called wave-noise, although “noise” is a bit of a misnomer) was a well-known phenomenon at radio

wavelengths, but its nature and even reality at optical wavelengths were seriously debated in the 1950s. Hanbury Brown & Twiss [1, 2] conclusively demonstrated in a series of papers how the phenomenon is firmly rooted in both theory and experiment. The intensity fluctuations can be interpreted in a semi-classical sense as the superposition of light waves at different frequencies producing beats. The fluctuations can also be interpreted in a quantum mechanical sense as an effect related to so-called photon bunching [3]. At optical wavelengths, the resulting fluctuations are much smaller than the shot-noise component of a (recorded) light beam. Given that shot-noise is random, any coherence of different light beams is solely determined by the intensity fluctuation effect. Hanbury Brown et al. [4] measured the stellar diameter for 32 stars using a dedicated stellar intensity interferometer stationed at Narrabri, Australia. Their pioneering experiments constituted the first successful stellar diameter measurements after the Michelson & Pease experiments. We will discuss in this contribution the potential of future Cherenkov Telescope Arrays for a revival of intensity interferometry as a mainstream high angular resolution imaging technique in astronomy.

## 2. Basic differences between Michelson and Intensity interferometry

All modern interferometers in operation are based on the principle of Michelson stellar interferometry. It provides a measure of the spatial coherence of two light beams by using the fringe contrast (visibility) of the beams' interference pattern. The technique requires highly accurate metrology to correct for path differences between the beams, which is on the order of the wavelength of light itself. Active correction of the optics (adaptive optics, tip-tilt) are required in order to make the otherwise corrugated wave front planar. Light beams are made to interfere, and allow in principle the determination of the modulus and phase of the complex visibility. In practise however, atmospheric limitations corrupt the phase (the fringes wander over the detector), and in broad-band interferometric observation a quadratic visibility estimator ( $VV^*$ ) is generally employed eliminating the corrupted phase, but at the same time introducing a bias in the estimator that needs to be taken care of, e.g., [5, 6]. In spectrally resolved observations a linear visibility estimator can be employed, thanks to the achromatic nature of the atmospheric disturbances, and relative phase can be retrieved. Absolute phase information with ground based interferometers can be obtained by simultaneously observing a phase reference star [7], or by exploiting the principle of closure phase when working with more than two telescopes, see [8].

Intensity interferometry provides a measure of the square of the Michelson fringe visibility. This fundamental difference is the basis for some of its technical advantages. It is virtually insensitive to atmospheric and instrumental instabilities as no actual waves are interfered. The technique can thus make do with relatively coarse light collectors and long baselines. The signals from each receiver can be electronically recorded and correlated after detection. The correlation of the multiple signals measured by a telescope array can thus all be determined for all possible pairs, and maybe even higher order correlations can be exploited. The coherence length is set by the length of the frequency beats (wave group) which is of order cm rather than nm (depending on bandwidth), alleviating the strong constraints on accurate delay tracking.

It is however less sensitive in measuring coherence than Michelson interferometry, as the sought fluctuations are very small relative to the shot-noise of the photon stream. However, without stringent requirements for the light collectors, the decreased sensitivity can be offset by large coarse mirrors in order to maximise photon collection. In addition [9, 10] have shown that under certain conditions higher order correlations will increase the sensitivity (see [11]). A second drawback is no phase information is contained within the measurement. Although this does not impede the measurement of centro-symmetric objects (indeed as was done with the Narrabri Stellar Intensity Interferometer), it has been shown that the phase can be recovered using correlations between more than two signals [12, 13]. Also superimposing a coherent beam

from a known reference source on the light beam of the target source would allow the recovery of the phase [12], see also [14, 15].

### 3. IACT array as an optical intensity interferometer

Imaging Air Cherenkov Telescope (IACT) Arrays are multi-telescope arrays designed to image air showers that are produced by high energy particles and  $\gamma$ -ray photons ( $> 10$  GeV) that impinge on the earth's atmosphere. The air showers consist of secondary particles some of which carry electrical charge and produce Cherenkov light. As the Cherenkov radiation is faint (depending on the energy of the incident particle/photon), large collecting areas are required to obtain decent signal-to-noise ratios. The flash of Cherenkov radiation produced is also very brief (a few nanoseconds) and fast photon counting detectors are therefore mandatory. The advantage of employing telescope arrays in air-shower observations is the ability to reconstruct the spatial geometry of the shower in the earth's atmosphere. This allows one to make a distinction between cosmic ray showers and  $\gamma$ -ray showers, and also to find the spatial direction of the incident particle/photon, thus obtaining angular information on the galactic or extragalactic source. In short, IACTs aim to determine the energy and the astrophysical source of  $\gamma$ -ray photons by observing the optical light of induced Cherenkov radiation. It should be clear that the basic technical specifications of an IACT array as touched upon here are very similar to the ones of an Intensity Interferometer as briefly described in the previous section. A more detailed description of the components of IACT arrays relevant for II (fast photon detection, signal communication, correlators) can be found in [16].

Currently, there are two major and successful IACT arrays operational. The H.E.S.S. array [17] consists of 4 telescopes of  $108\text{ m}^2$  each. They are arranged in a square with 120 m side length. The VERITAS [18] array is similar and also consists of 4 telescope with  $110\text{ m}^2$  light collecting area. In contrast to HESS, it has variable baselines ranging from 34 to 109 metres. HESS will be upgraded to HESS II with one extra 30 m dish telescope placed at the centre of the configuration, its completion foreseen for the 4th quarter of 2009. Future IACT projects are currently under study, such as AGIS<sup>1</sup> and CTA<sup>2</sup>, and aim at increasing the number of telescopes up to 100, each with a  $\sim 100\text{ m}^2$  light collectors arranged over an area covering  $1\text{ km}^2$  or more. These envisioned projects (expected to be operational around 2015) would not only benefit the resolving power and sensitivity for the high-energy science purposes of IACTs, but they are in harmony with the requirements of a more sensitive intensity interferometer with a higher angular resolution and denser (u,v)-coverage [16]. Future IACTs will offer thousands of baselines from 50 m to at least 1 km and when used as an intensity interferometer may attain angular resolution down to a few tens of  $\mu$ -arcseconds.

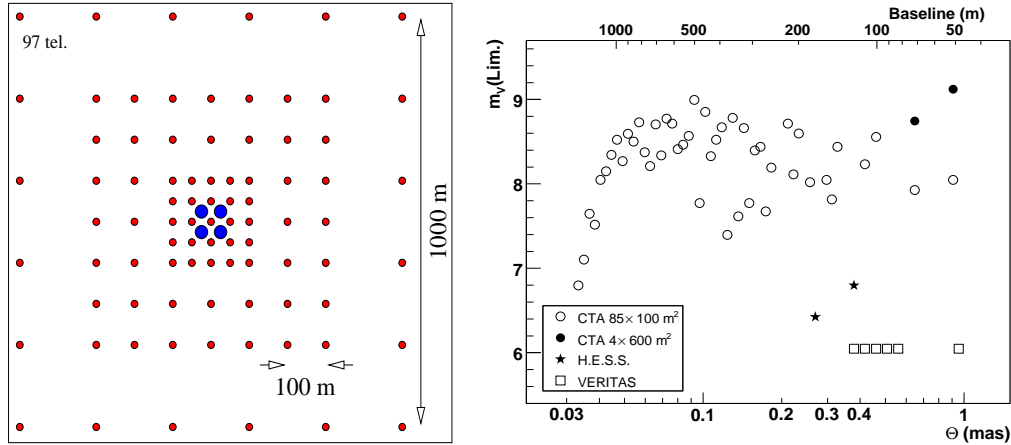
### 4. Science for II

Limiting  $m_v$  of the CTA concept is illustrated in the right panel of Fig.1 with simulated performance that meet the goal sensitivity for  $\gamma$ -ray astronomy [19]. Targets are limited to a  $m_v \approx 8.5^m$  for a  $S/N = 5$ , and a 5 hours integration in case of 50% visibility (see [11]). These specifications allow important interferometry studies regarding binary stars, stellar radii and pulsating stars with unprecedented resolution on  $\mu$ -arcsecond scales. We highlight three potential science cases below.

**Star formation** Key questions relating to the physics of mass accretion and pre-main sequence (PMS) evolution can be addressed by means of very high resolution imaging as provided by the next generation IACTs and II. They involve the absolute calibration of PMS tracks, the

<sup>1</sup> <http://gamma1.astro.ucla.edu/agis/>

<sup>2</sup> <http://www.mpi-hd.mpg.de/hfm/CTA>



**Figure 1.** *Left:* Proposed lay-out for the future CTA. Small red dots are the 85 100 m<sup>2</sup> dishes, large blue dots are the four 100 m<sup>2</sup> dishes (adapted from [19]). *Right:* Sensitivity estimate as function of the 48 non-redundant baselines for a  $5\sigma$  detection, in a 5 hr integration on a centrosymmetric object with 50% visibility. Final values depend on signal bandwidth and CTA design details, see [16].

mass accretion process, continuum emission variability, and stellar magnetic activity. The technique may allow us to resolve spot features on the stellar surface. Hot spots deliver direct information regarding the accretion of material onto the stellar surface. Cool spots, on the other hand, may cover 50% of the stellar surface, and they are the product of the slowly decaying rapid rotation of young stars. Imaging them will constrain ideas regarding the interplay of rotation, convection, and chromospheric activity as traced by cool spots. It may provide direct practical application as the explanation for the anomalous photometry observed in young stars [20].

In practise, about 50 young stars with  $m_v < 8^m$  are within reach of future IACTs. In the last decade several young coeval stellar groups have been discovered in close proximity ( $\sim 50$  pc) to the sun. Famous examples are the TW Hydra and  $\beta$  Pic comoving groups. The majority of the spectral types within reach range between A and G-type. Their ages lie within the range 8 to 50 Myr (see [21] for an overview). The age intervals ensures that a substantial fraction of the low-mass members are still in their PMS contraction phase. Measurement of their angular size can be used in the calibration of evolutionary tracks, fundamental in deriving the properties of star forming regions and young stellar clusters. The proximity of the comoving groups ensures that their members are bright. Their proximity renders the comoving group also relatively sparse making them very suitable, unconfused targets despite the large optical PSF of a few arcminutes. The sparseness is also the reason for incomplete group memberships, making it likely that the number of young stars close to the sun will increase with the years to come.

**Distance scale and pulsating stars** Measuring diameters of Cepheids is a basic method with far reaching implications. A radius estimate of a Cepheid can be obtained using the Baade-Wesselink method. The Baade-Wesselink method relies on the measurement of the ratio of the star size at times  $t_1$  and  $t_2$ , based on the luminosity and colour. Combined with a simultaneous measurement of the radial velocity, this method delivers the difference in the radius between  $t_1$  and  $t_2$ . With the known difference and ratio of the radius at two times, one can derive the radius of the Cepheid. Combining II angular size measurement with the radius estimate one obtains

the distance to the Cepheid (see [22]). This makes possible the calibration of the all important Cepheid period-luminosity relation using local Cepheids. A count of Cepheids observed with *Hipparcos* [23] shows that at least 60 Cepheids with  $m_v < 8^m$  are in reach with future IACTs.

**Rapidly rotating stars** As a group, classical Be stars are particularly well-known for their close to break-up rotational velocities as deduced from photospheric absorption lines. In addition the stars show Balmer line emission firmly established as due to gaseous circumstellar disks, that appear and disappear on timescales of months to years. These two properties are somehow related, but many open questions regarding the detailed physical processes at play exist.

The Be-phenomenon is an important phenomenon given the number of stars and stellar physics involved (fraction of Be stars to normal B-type peaks at nearly 50% for B0 stars, [24]). Absorption lines will however never provide the final answer to their actual rotational velocity due to strong gravity darkening at the equator and brightening at the pole areas. Direct measurement of the shape of the rotating star is not hampered by gravity darkening, and provides a direct indication of the rotational speed (see, e.g.,  $\alpha$  Eri with the VLTI, [25]). The Be star disk formation and dissolution activity is little understood. Photometric observations of Be star disks seem to indicate that they may actually evolve into ring structures before disappearing into the interstellar medium (e.g. [26]). The disk's Bremsstrahlung can constitute  $\sim 30\%$  of the total light in V-band [24].

There are about 300 Be stars<sup>3</sup> brighter than  $m_v = 8^m$ , roughly corresponding to a distance limit of 700 pc. Signifying that Be star phenomena can be probed in depth with IACT based II.

## 5. Concluding remarks

Technical requirements for a relatively sensitive and  $\mu$ -arcsecond resolution synthesis intensity interferometer go hand in hand with the designs for next generation Air Cherenkov Telescope arrays. This prompts close study of the possibilities in designing and building a IACT instrument that incorporates the II capability. In principle there is no competition between the two modes, as  $\gamma$ -ray observations need to be executed when the moon is less than half full. This leaves half the available night time of an IACT for interferometric observations.

The renewed interest in II has resulted in the formation of an IAU working group on intensity interferometry. Laboratory experiments are performed to test and demonstrate the various aspects of II integrated in a IACT. A pair of 3-m telescopes is now available in Utah, USA (Star base Utah 2008<sup>4</sup>) for testing the techniques in a realistic astronomical environment.

In conclusion, the time is now to assess the applicability of II as a future high resolution imaging mode that allows science to enter the realm of astrophysics on  $\mu$ -arcsecond angular scales.

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